

Development of Bacteria and Benthic Total Maximum Daily Loads: A Case Study, Linville Creek, Virginia

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ABSTRACT

Two total maximum daily load (TMDL) studies were performed for Linville Creek in Rockingham County, Virginia, to address bacterial and benthic impairments. The TMDL program is an integrated watershed management approach required by the Clean Water Act. This paper describes the procedures used by the Center for TMDL and Watershed Studies at Virginia Tech to develop the Linville Creek TMDLs and discusses the key lessons learned from and the ramifications of the procedures used in these and other similar TMDL studies. The bacterial impairment TMDL was developed using the Hydrological Simulation Program—Fortran (HSPF). Fecal coliform loads were estimated through an intensive source characterization process. The benthic impairment TMDL was developed using the Generalized Watershed Loading Function (GWLF) model and the reference watershed approach. The bacterial TMDL allocation scenario requires a 100% reduction in cattle manure direct-deposits to the stream, a 96% reduction in nonpoint-source loadings to the land surface, and a 95% reduction in wildlife direct-deposits to the stream. Sediment was identified as the primary benthic stressor. The TMDL allocation scenario for the benthic impairment requires an overall reduction of 12.3% of the existing sediment loads. Despite the many drawbacks associated with using watershed-scale models like HSPF and GWLF to develop TMDLs, the detailed watershed and pollutant-source characterization required to use these and similar models creates information that stakeholders need to select appropriate corrective measures to address the cause of the water quality impairment when implementing the TMDL.

THE TOTAL MAXIMUM DAILY LOAD (TMDL) program is a watershed management approach required by the Clean Water Act that integrates watershed planning with water quality assessment and protection. Water bodies in violation of state water quality standards are referred to as “impaired.” According to the USEPA, over 40% of assessed waters in the United States do not meet water quality standards and thus are impaired. This amounts to over 20 000 individual river segments, lakes, and estuaries and includes approximately 480 000 km of rivers and shorelines and approximately 2 million ha of lakes, polluted mostly by sediments, excess nutrients, and harmful microorganisms (USEPA, 2004). Under the Clean Water Act, pollutant-specific TMDLs are required for impaired water bodies. Virginia’s 2004 305b report (Virginia Department of Environmental Quality, 2004a) presented the results of the assessment of the water

quality in approximately 22.5% of the state’s free-flowing streams and rivers for which sufficient data were available to assess at least some designated uses. Of the approximately 31 076 km (19 310 miles) assessed, some 18 129 km (11 265 miles) of streams and rivers were classified as impaired and require a TMDL.

A TMDL is a quantitative representation of all the contributions of a particular pollutant to a water body and is defined as:

$$\text{TMDL} = \Sigma \text{WLAs} + \Sigma \text{LAs} + \text{MOS} \quad [1]$$

where ΣWLA (waste load allocations) represents the sum of all point loadings, the ΣLA (load allocations) represents the sum of all nonpoint-source loadings, and MOS represents a margin of safety. The sum of these terms constitutes the TMDL and represents the loading of the constituent of interest that the water body can assimilate without violating the applicable state water quality standard. For the USEPA to approve a TMDL, all major point and nonpoint sources of the offending pollutant must be identified and quantified. Developing a TMDL often involves a study that first identifies the sources of the pollutants causing water quality impairments, quantifies the pollutant contribution from each source (or source category in the case of nonpoint-source pollution), and determines the pollutant reduction from each source required to meet applicable state water quality standards. Hydrologic and water quality models are often used to develop the necessary TMDL pollutant reduction scenarios.

Researchers affiliated with the Center for TMDL and Watershed Studies (hereafter the Center) and in the Biological Systems Engineering Department at Virginia Tech were contracted by the Virginia Department of Environmental Quality (VADEQ) to develop TMDLs for Linville Creek for violations of the Bacteria and General Standard for Aquatic Life (benthic) impairments (Mostaghimi et al., 2003). The researchers used two modeling tools to develop the two TMDLs for Linville Creek in Rockingham County, VA: the Hydrological Simulation Program—Fortran (HSPF) was used for the bacteria impairment TMDL, and the Generalized Watershed Loading Function (GWLF) model was used for the benthic impairment TMDL. The objective of this paper is to describe the processes used to develop the Linville Creek TMDLs as a case study and communicate some of the key lessons learned from these and other similar TMDL studies conducted by the Center.

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Abbreviations: GWLF, Generalized Watershed Loading Function; HSPF, Hydrological Simulation Program—Fortran; LA, load allocation; MOS, margin of safety; RBP II, Rapid Bioassessment Protocol II; TMDL, total maximum daily load; VADEQ, Virginia Department of Environmental Quality; WLA, waste load allocation.

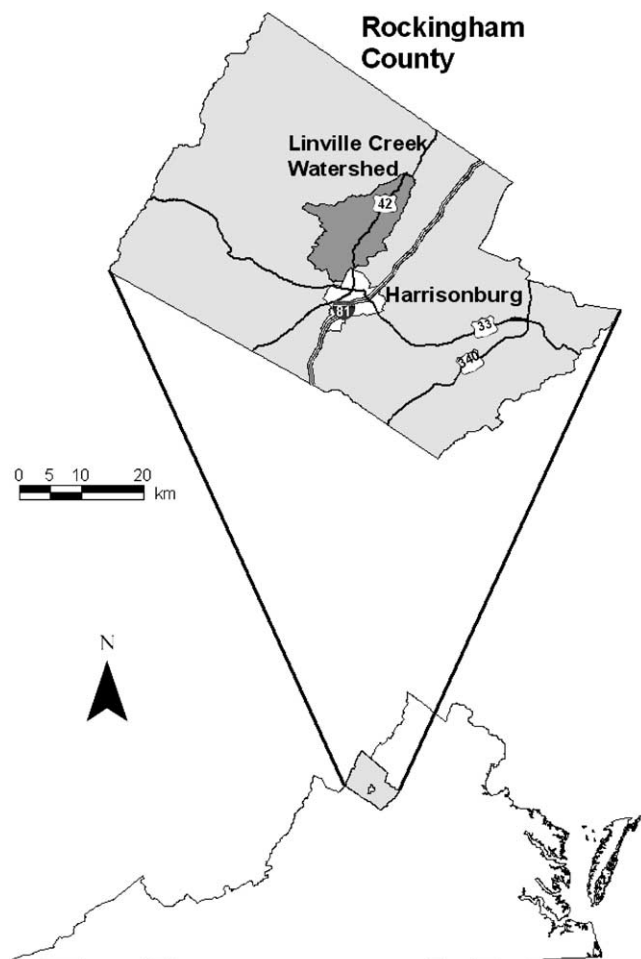


Fig. 1. Location of the Linville Creek watershed.

MATERIALS AND METHODS

Located in Rockingham County, Virginia, the Linville Creek watershed (11 998 ha) is just north of the city of Harrisonburg (Fig. 1). Linville Creek is a tributary of the North Fork of the Shenandoah River. The North Fork of the Shenandoah River joins with the South Fork of the Shenandoah River to become the Shenandoah River, which in turn, is a tributary of the Potomac River. The Potomac River discharges into the Chesapeake Bay. Linville Creek flows through a mainly agricultural watershed, located in a rolling valley with the Blue Ridge Mountains to the east and the Appalachian Mountains to the west. Pasture is the main land use in the Linville Creek watershed, comprising 49% of the total area, with cropland and forest accounting for 21% and 16%, respectively. Residential and urban developments, the remaining 9%, are spread throughout the watershed with a slight concentration around the town of Broadway near the outlet. A USGS flow gaging station (01632082) is located in the northern part of the watershed near the mouth of Linville Creek at an elevation of 313.7 m (Fig. 2). Figure 2 also shows the location of the DEQ benthic and ambient water quality monitoring stations. Mean daily streamflow at this gage ranged from 0.3 to 8.3 m³/d, with an overall daily mean of 1.0 m³/d during the 1993–2001 period of record. Average annual precipitation in the watershed was 89.7 cm for the same period.

Bacteria Impairment Total Maximum Daily Load

Water quality samples collected by the VADEQ in Linville Creek from November 1993–June 1997 indicated that 50% of

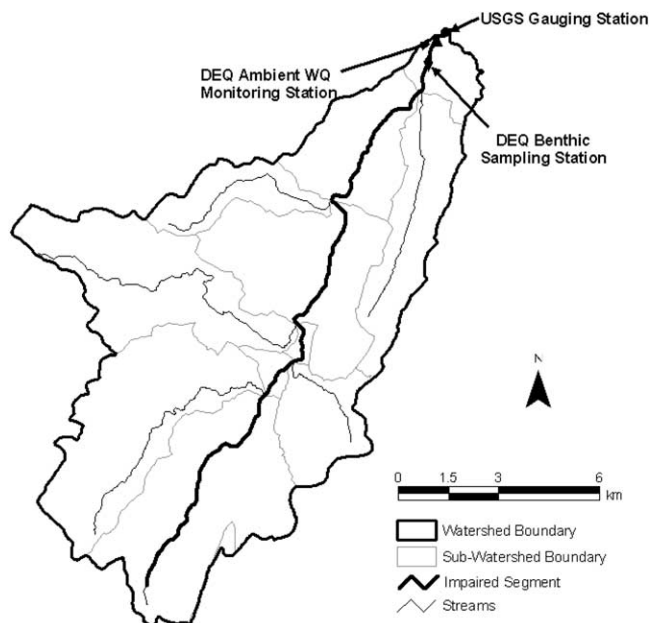


Fig. 2. Locations of Virginia Department of Environmental Quality (DEQ) and U.S. Geological Survey (USGS) monitoring stations on the impaired segment of Linville Creek.

the samples violated the instantaneous water quality standard for fecal coliform applicable at the time (1000 colony forming units [cfu] per 100 mL). Due to the frequency of water quality violations, Linville Creek was assessed as not supporting the Clean Water Act's Swimming Use Support Goal for the 1998 305(b) report, and it was placed on Virginia's 1998 303(d) list of impaired water bodies for fecal coliform (Virginia Department of Environmental Quality, 1998). A TMDL was developed as a result of this listing. We used the Hydrological Simulation Program—Fortran (HSPF) (Duda et al., 2001) to develop the Linville Creek bacteria impairment TMDL. The TMDL was developed for the new water quality standard for bacteria (9 VAC 25-260-170; Virginia Department of Environmental Quality, 2004b), which states that the calendar-month geometric mean concentration of *Escherichia coli* shall not exceed 126 cfu/100 mL, and that no single sample can exceed a concentration of 235 cfu/100 mL.

Source Assessment

Potential fecal coliform sources in the Linville Creek watershed were characterized using information from the following sources: Virginia Department of Environmental Quality, Virginia Department of Conservation and Recreation, Virginia Department of Game and Inland Fisheries, Virginia Cooperative Extension, USDA Natural Resources Conservation Service, stakeholder input, watershed reconnaissance and monitoring, published information, and professional judgment. Land surface and direct-deposit fecal coliform load inputs needed for the HSPF model were generated using an in-house spreadsheet-based bacteria source load calculator (BSLC) (Zeckoski et al., 2005). Direct-deposit loads include wildlife and cattle defecating directly in the stream and human-source straight pipes. The BSLC uses externally generated inputs, such as land use distribution and livestock, wildlife, and human population estimates, to calculate monthly bacterial loadings to the land surface and hourly bacterial loadings deposited directly in the water body. The BSLC was developed using Visual Basic for Applications (VBA) in Microsoft Excel. The BSLC greatly simplifies the creation of data files needed by

Table 1. Wildlife habitat areas and population estimates.

Wildlife type	Habitat	Population density
		animal/ha-habitat
Deer†	entire watershed	0.019
Raccoons†	183-m buffer around streams and impoundments	0.028
Musk rats‡	20-m buffer around streams and impoundments in forest and cropland	1.11
Beavers§	91-m buffer streams and impoundments in forest and pasture	0.006
Geese	91-m buffer around main streams and impoundments	0.032 (off season), 0.044 (peak season)
Wood duck#	91-m buffer around main streams and impoundments	0.025 (off season), 0.038 (peak season)
Wild turkey††	entire watershed except urban and farmstead	0.004

† MapTech (2000).

‡ Modified from MapTech (2000) to better quantify muskrat populations in Linville Creek.

§ Density calculated from colony size estimates from Missouri Department of Conservation (1997) and colony/ha estimates by Stromayer (1999); habitat modified from estimates by MapTech (2000).

|| Moyer and Hyer (2003).

Habitat area from Moyer and Hyer (2003); population density modified from Moyer and Hyer (2003).

†† Brannan et al. (2002).

HSPF (or other similar models) and provides consistency in data development and processing.

Based on the source assessment and user-input land uses, the BSLC was used to calculate the amount of bacteria produced in different locations and on different land uses (e.g., livestock confinement, pasture, forest). Bacteria production that was deposited on the land surface was estimated on a monthly basis to account for seasonal variability in livestock and wildlife population estimates and livestock management and production practices. Livestock population estimates and management and production practices, such as the fraction of time cattle spend in confinement or on pastures, the amount of manure held in storage and subsequently land applied, and spreading schedules for manure application, were considered on a monthly basis (Mostaghimi et al., 2003). Manure timing and application rates for both liquid and dry manures were based on application rates and timing guidelines specified by Virginia's Department of Conservation and Recreation nutrient management planning guidance (Virginia Department of Conservation and Recreation, 1993). Hourly direct-deposit fecal coliform loading by cattle to streams was calculated for the percentage of pastures adjacent to streams where no fencing was present.

The most recent county-wide Agricultural Census published by the USDA (2002) was used to develop initial dairy and beef cattle population estimates. Additionally, approximately 90% of the dairy producers in the watershed were contacted directly in an attempt to refine the livestock population estimates. A representative from the local Headwaters Soil and Water Conservation District and the local Virginia Cooperative Extension agent assisted in refining population estimates for beef and poultry. Confined animal feeding operation VADEQ permits were consulted where applicable.

Wildlife contribute to fecal coliform loads to pasture, cropland, and forest land uses. They also direct-deposit in the water body. A direct inventory of the wildlife population was neither practical nor feasible; therefore, an indirect wildlife population estimation approach based on available suitable habitat for each species thought to be present in the watershed was used. First, suitable habitat areas were defined for individual wildlife species, typically within a certain buffer around water bodies within a given type of land use (Table 1). A geographic information system (GIS) was used to create spatial buffers and to calculate the suitable habitat area available in each subwatershed. Wildlife populations were calculated as the product of the suitable habitat area for each species within each subwatershed and values of typical species densities (Table 1). These initial estimates were adjusted as deemed appropriate based on watershed reconnaissance and consultation with Virginia Department of Game and Inland Fisheries personnel and local stakeholders during the public meetings

held in conjunction with developing the TMDL. Factors including habitat, range, migration, and estimated fraction of time spent in the stream are considered when estimating wildlife fecal coliform loads. As with livestock loads, wildlife land surface loads varied monthly and direct-deposit stream loads varied hourly.

Nonagricultural nonpoint-source bacteria loads included failing septic systems and pet waste. Locations of an estimated 1499 unsewered households were identified using 1999 E-911 digital data from Rockingham County. Each unsewered household was classified into one of three age categories (pre-1967, 1967–1987, and post-1987) based on USGS 7.5-min topographic maps and their revision dates. Of the houses located within 45 m of streams, 10% of the older houses and 2% of houses in the middle age range were assumed to discharge their sewage through a pipe directly to the stream (an illegal straight pipe discharge). It was assumed that septic system failure rates for the remainder of the houses in the pre-1967, 1967–1987, and post-1987 age categories were 40, 20, and 3%, respectively (Mostaghimi et al., 2000). Estimates of these failure rates were also supported by the Holmans Creek Watershed Study (a watershed located just north of Linville Creek), which found that over 30% of all septic systems checked in the watershed were either failing or not functioning at all (Science Applications International Corporation, 2001). Effluent from a failing septic system that rises to the land surface can be carried away with runoff during storm events. The amount of bacteria available on residential land surface for loss in surface runoff is based on the number of houses within a subwatershed in each age category, the specified failure rate for a particular age dwelling, the amount of bacteria produced by a human per day on average, and the average number of people per house as estimated from U.S. Census data. To account for pet contributions, each household was assumed to have a standard unit pet that produced the fecal coliform equivalent to one average-sized dog (Mostaghimi et al., 2003).

Hydrological Simulation Program—Fortran Modeling

The Hydrological Simulation Program—Fortran (HSPF) was used to simulate the fate and transport of fecal coliform bacteria in the Linville Creek watershed. The HSPF model simulates nonpoint-source runoff and pollutant loadings, performs flow routing through streams, and simulates in-stream water quality processes (Duda et al., 2001). The HSPF model requires a wide variety of input data to describe hydrology, water quality, and land-use characteristics of the watershed. For modeling purposes, the Linville Creek watershed was divided into 11 subwatersheds (Fig. 2). Hydrology parameters were defined for every land-use category for each subwatershed. Within HSPF a function table (FTABLE) is required

Table 2. Linville Creek Hydrological Simulation Program—Fortran (HSPF) hydrology simulation calibration and validation results.

Parameter	Calibration (September 1987–December 1992)			Validation (January 1993–September 2001)		
	Observed	Simulated	Error	Observed	Simulated	Error
	cm/yr		%	cm/yr		%
Total runoff	24.4	22.6	−7.3	34.3	32.3	−6.3
Summer† runoff	3.6	3.1	−14.0	5.6	5.3	−4.8
Winter‡ runoff	7.4	7.1	−4.0	10.9	10.2	−7.5

† June–August.

‡ December–February.

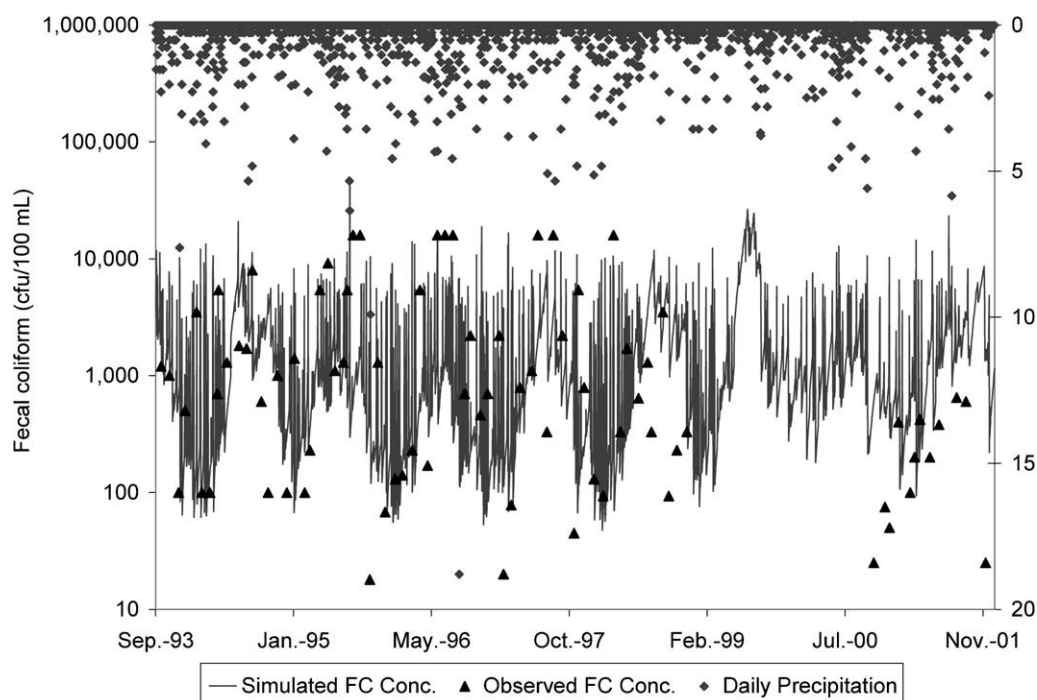
to describe the relationship between water depth, surface area, volume, and discharge for each subwatershed (Donigan et al., 1995). These parameters were estimated by surveying representative channel cross-sections in each subwatershed. Values for other hydrologic parameters were estimated based on local conditions when possible. Otherwise, the default parameters provided within HSPF were used (Mostaghimi et al., 2003).

The hydrologic component of the Linville Creek HSPF model was calibrated using flow data from the USGS station on Linville Creek located near Broadway, Virginia (01632082). The drainage area monitored at this station is 11 785 ha and the available period of record was August 1985 through September 2001 (approximately 16 yr). Hourly precipitation data required by the model were obtained from the Dale Enterprise weather station located about 2.4 km southwest of the watershed. Since hourly data for other meteorological parameters needed by HSPF were not available, the Watershed Data Management Utility program (WDMUtil) (USEPA, 2005) was used to disaggregate available daily meteorological parameters. Many parameters were not available at Dale Enterprise (e.g., wind speed, dew point temperature, percent sun); therefore, daily data from Lynchburg Airport (Virginia) and Elkins Airport (West Virginia) were used to complete the meteorological data set required for running HSPF. The Lynchburg and Elkins stations were 142 km south-southwest and 98 km northwest of the Linville Creek watershed, respectively.

The hydrology calibration period selected for Linville Creek was September 1987 to December 1992. The HSPF decision

support system software HSPEXP (Lumb and Kittle, 1994) was used to develop a calibrated HSPF model for the Linville Creek watershed. The HSPEXP system provides guidance on parameter adjustment during the calibration process. The calibration of the HSPF hydrology parameters resulted in simulated flows that accurately matched the observed data for Linville Creek (Table 2). There was good agreement between the observed and simulated stream flow indicating that the model adequately represented the hydrologic characteristics of the watershed. Percent error for each variable was within the criteria suggested by HSPEXP (Mostaghimi et al., 2003). The calibrated model was then used to predict runoff for a different time period (the validation period was January 1993 to September 2001) to evaluate the appropriateness of the calibrated parameters (Table 2). There was good agreement between the observed and simulated stream flow for the validation period, indicating that the calibrated parameters adequately represent the characteristics of the watershed for time periods outside the calibration period (Mostaghimi et al., 2003).

After the hydrologic calibration and validation were completed, the water quality component of HSPF was calibrated using seven years of fecal coliform data, November 1993 to September 2001. A comparison of simulated and observed fecal coliform loadings in the stream indicated that the model adequately simulated the fate of fecal coliform in the watershed (Fig. 3). Because fecal coliform data are collected on a


Fig. 3. Linville Creek fecal coliform (FC) calibration for existing conditions.

monthly basis, insufficient data were available to conduct a validation of the water quality model.

Bacteria transport from the land surface in runoff was modeled in HSPF using a wash-off factor “WSQOP” (the wash-off factor is a calibrated parameter). When runoff events greater than or equal to 6.4 cm/h occurred, 90% of the land-surface bacteria load was removed via surface runoff. The accumulation of bacteria on the land surface before wash-off was limited using the monthly maximum constituent accumulation table “MON-SQOLIM” to simulate die-off. Subsurface transport of bacteria via interflow and ground water flow was simulated in HSPF as if the waters from these pathways had a constant concentration of 30 and 20 cfu/100 mL, respectively. This approach is the result of guidance from the Virginia Department of Environmental Quality (2003a). Additional state agency guidance specifies that bacteria TMDLs are to be developed by modeling bacteria as a completely dissolved solute. The authors (as well as other TMDL developers) have questioned this approach and have initiated research investigating the effect of this directive on the resulting TMDL load and associated load reductions. The VADEQ further directs TMDL developers to model water quality using fecal coliform loadings as the bacteria source in the watershed and to then apply a translator equation to convert daily average fecal coliform concentrations output by the model to daily average *E. coli* concentrations (Virginia Department of Environmental Quality, 2003b). The VADEQ developed translator equation is:

$$E. coli \text{ concentration} = 2^{-0.0172} \times (\text{FC concentration})^{0.91905} \quad [2]$$

where the bacteria concentrations (FC and *E. coli*) are in cfu/100 mL.

Once developed, the Linville Creek HSPF model was used to simulate bacteria loads to the stream for a representative hydrologic period, in this case from September 1987 to December 2001. Once this baseline was established, the model was used to develop alternative bacteria source reduction scenarios that met the state's water quality standard using the same representative hydrologic period. For the TMDL, daily *E. coli* loads were obtained by multiplying the average daily simulated flow by *E. coli* concentrations calculated using Eq. [2]. Annual loads were obtained by summing the daily loads and dividing by the number of years in the allocation period. The bacteria source reductions and the resulting loads were used to set the Linville Creek TMDL load.

Benthic Impairment Total Maximum Daily Load

Many states monitor streams for some type of biological impairment. In Virginia, biological monitoring is conducted by the VADEQ using the USEPA's Rapid Bioassessment Protocol II (RBP II) to assess the health of the benthic macroinvertebrate community (Barbour et al., 1999). Evaluations of monitoring data from the program focus on the benthic (bottom-dwelling) macroinvertebrates (insects, mollusks, crustaceans, and annelid worms large enough to see with the naked eye) and are used to determine whether or not a stream segment is supporting Virginia's narrative General Standard for Aquatic Life (9 VAC 25-260-20 A) (Virginia Department of Environmental Quality, 2004b).

Changes in water quality generally result in changes in the types and numbers of the benthic organisms that live in streams and other water bodies. Besides being the major intermediate constituent of the aquatic food chain, benthic macroinvertebrates are “living recorders” of past and present water quality conditions. This is due to their relative immobility and their

variable sensitivity to the diverse contaminants that can be introduced into streams. The community structure and diversity of these organisms provides the basis for the biological analysis of water quality. Qualitative and semiquantitative biological monitoring has been conducted by VADEQ since the early 1970s. The USEPA RBP II was employed beginning in the fall of 1990 to utilize standardized and repeatable methodology for the biological analysis. For any single sample, the RBP II produces water quality ratings of “non-impaired,” “slightly impaired,” “moderately impaired,” and “severely impaired.” In Virginia, benthic samples are generally taken and analyzed twice a year, in the spring and fall.

The RBP II procedure evaluates the benthic macroinvertebrate community by comparing ambient monitoring network stations to reference sites. A reference site is one that has been determined to be representative of a natural, non-impaired water body. The RBP II evaluation also accounts for the natural variation noted in streams in different ecoregions (regions that share characteristics such as meteorological factors, elevation, plant and animal speciation, landscape position, and soils). One additional product of the RBP II evaluation is a habitat assessment. This assessment provides information on the comparability of a stream segment near each stream station to a segment near the reference stream station. In Virginia, any stream segment with an overall RBPII rating (involving more than one RBP II survey) of “moderately impaired” or “severely impaired” during a given assessment period is placed on the state's 303(d) list of impaired streams (Virginia Department of Environmental Quality, 1998).

Of the four RBPII assessments performed on Linville Creek between October 1994 and May 1996 (the relevant period of record for the 1998 303(d) assessment period), two received a rating of moderately impaired. As a result, Linville Creek was placed on Virginia's 303(d) list in 1998 (Virginia Department of Environmental Quality, 1998). The RBPII ratings for the period of record from October 1994 through May 2002 (includes data up to the time when the TMDL was developed) are shown in Fig. 4.

Stressor Analysis

Because a benthic impairment is based on an assessment of benthic macroinvertebrates, rather than on specific pollutant concentrations, the cause of a benthic impairment is not explicitly identified. Consequently, a critical task in developing a TMDL to address a benthic impairment is identifying the cause of the impairment through a process known as stressor analysis. The process outlined in the USEPA's *Stressor Identification Guidance Document* (USEPA, 2000) was used to identify the critical stressor for Linville Creek. A list of candidate stressors was developed from published literature and stakeholder input. Chemical and biological monitoring data provided additional evidence to assist in supporting or eliminating potential candidate stressors. Logical pathways were explored between observed characteristics of the benthic community, potential stressors, and intermediate steps or interactions that would be consistent in establishing a cause-and-effect relationship with each candidate stressor. Common candidate benthic stressors are suspended solids, temperature, pH, toxics, organic matter, nutrients, and sediment.

The Reference Watershed Approach

Virginia, like many other states, does not have numeric criteria for many potential benthic community stressors, like sediment. Therefore, an alternative approach must be used to establish the numeric pollutant or stressor load required

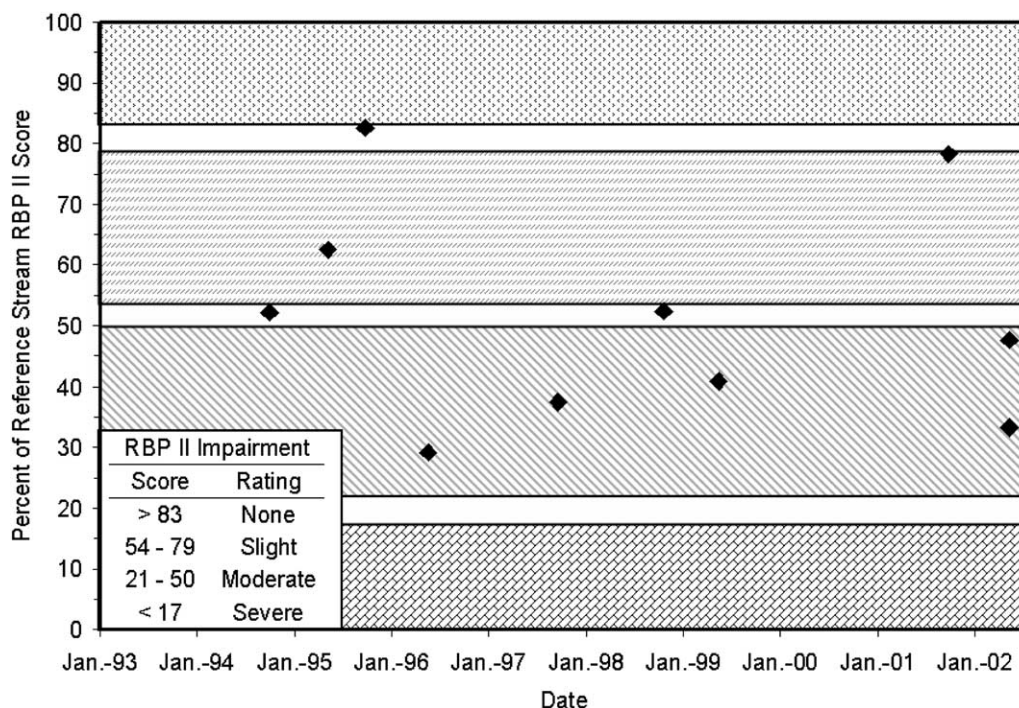


Fig. 4. Linville Creek Rapid Bioassessment Protocol II (RBP II) results.

for the TMDL. The reference watershed approach was the alternative used with Linville Creek. The reference watershed approach entails selecting a watershed with a stream that is not biologically impaired and is comparable to the impaired watershed in terms of land use, topography, precipitation, and other characteristics. These watershed characteristics and descriptions of pollutant sources or pollutant-generating processes are input into a water quality model to simulate hydrologic and pollutant-loading responses from the impaired and reference watersheds. The unit-area pollutant load in the reference watershed then becomes the TMDL target-load in the impaired watershed. The basic assumption of the reference watershed approach is that if the unit-area pollutant load in the impaired watershed is reduced to the same level as in the reference watershed, then the health of the benthic community in the impaired watershed will be restored. Additional details on the reference watershed approach are available from Wagner (2004).

The reference watershed approach was used to define the sediment target-load for the benthic impairment TMDL for Linville Creek (Mostaghimi et al., 2003). Potential reference watersheds were identified that were in the same Valley and Ridge physiographic region of Virginia as Linville Creek and that were classified as non-impaired based on VADEQ biological monitoring. Seven potential candidate reference watersheds were identified (Table 3). Of those, the Upper Opequon Creek watershed was selected as the TMDL reference watershed for Linville Creek. Land use distribution and watershed area were considered to be the most important characteristics when selecting a reference watershed. The Upper Opequon was the most similar to Linville Creek in these aspects. Perhaps most importantly, the dominant land use in both the Upper Opequon and Linville Creek watersheds was agricultural. Additional similarities included the nonforested soil erodibility (K-factor) and slopes.

Generalized Watershed Loading Function Modeling

The benthic impairment TMDL for the Linville Creek watershed was developed using sediment loads generated by the

Generalized Watershed Loading Function (GWLF) model. Although GWLF (Haith et al., 1992) was originally developed for use in ungaged watersheds, the BasinSim adaptation of the model (Dai et al., 2000) recommended hydrologic calibration of the model. Because observed daily flow data were available at both Linville Creek and Opequon Creek, hydrologic calibration was performed on both watersheds. To ensure comparability between the impaired and TMDL reference watersheds, GWLF hydrology parameters were calibrated for both watersheds in a consistent manner. The GWLF model for each watershed was calibrated for hydrology and then run for existing conditions over a 10-yr period from January 1988 to December 1997 for model validation and TMDL development purposes (Mostaghimi et al., 2003).

In-stream sediment loads were generated by surface runoff from both pervious and impervious areas, by channel erosion, and from permitted discharges. Pervious area sediment loads are modeled in GWLF through sediment detachment and modified universal soil loss equation (USLE) erosion algorithms. The GWLF model applies a sediment delivery ratio to the pervious area loads to estimate the sediment load at the watershed outlet. Impervious area sediment loads were modeled using an exponential buildup-washoff algorithm. Channel erosion was modeled within GWLF using the algorithms included in the AVGWF (ArcView GWLF) adaptation of the GWLF model (Evans et al., 2001). Channel erosion in GWLF was calculated as a function of daily stream flow volume and a regression coefficient that was based on the percentage of developed land, animal density, watershed-averaged soil erodibility, the watershed-averaged runoff curve number, and total stream length in each watershed. Sediment loads from point-source dischargers were calculated using total suspended sediment (TSS) concentrations and flow volumes. For existing loads from permitted Virginia Pollutant Discharge Elimination System (VPDES) facilities, available monthly discharge monitoring report (DMR) data reported by each facility were used to calculate average daily TSS loads. Sediment loads from general permit facilities were calculated as the

Table 3. Potential total maximum daily load (TMDL) reference watersheds and watershed characteristics.

Stream	Area	Land use distribution			Nonforested		Elevation	Population (2000)	
		Urban	Forested	Agricultural	K-factor†	Slope		Total	Nonsewered
	ha	%				%	m		%
Linville Creek	12 017	2	23	75	0.32	8.8	412	5 757	66
Upper Opequon Creek	15 045	5	35	60	0.30	5.6	224	19 809	82
Strait Creek	672	0	71	29	0.24	18.5	988	57	100
Stony Creek	19 768	1	87	12	0.27	11.7	507	3 112	68
Bullpasture River	28 495	0	81	18	0.25	7.7	765	527	100
Cowpasture River	56 604	0	86	14	0.26	13.8	748	994	100
Hays Creek	20 801	0	52	48	0.31	12.5	526	1 600	100
Jackson River	31 429	0	81	19	0.26	13.9	849	705	100

† Universal soil loss equation (USLE) soil erodibility factor (K-factor) determined from the geospatial STATSGO (STATE Soil GeOgraphic) database, dimensionless.

number of permits multiplied by the annual permitted TSS load for each permit.

The data used to evaluate model parameters were obtained from a variety of sources. Digital data were used wherever possible to enable parameter evaluation with ArcView 3.3 GIS software. Land use was obtained from the 1992 multi-resolution land characteristics (MRLC) data layer with modified land use classifications used by Virginia in its 2002 state-wide NPS pollution assessment (Yagow et al., 2002). County level soil surveys, 30-m digital elevation models (DEMs), and USGS National Hydrography Dataset (<http://nhd.usgs.gov>; verified 28 June 2005) stream layers were all used as part of the parameter evaluation process along with the guidance provided in the GWLF user's manual (Haith et al., 1992). Daily temperature and rainfall data for Linville Creek were calculated as a Thiessen-weighted average of data from the Dale Enterprise and Timberville stations, located approximately 2.4 km southwest and 23 km northeast of the center of the watershed, respectively. Daily temperature and rainfall were obtained for Upper Opequon Creek from two stations: Winchester WINC and Winchester 7 SE (both stations are approximately 4.8 km northwest of the watershed). Daily flow data from Linville Creek (01632082) and Upper Opequon Creek (01615000) USGS gaging stations were used in calibrating hydrologic parameters in the GWLF model. Hydrologic calibration results for both Linville and Upper Opequon Creeks are shown in Table 4. Livestock populations and locations obtained for the purpose of developing the Linville Creek bacteria impairment TMDL were used here to estimate livestock impact on channel erosion.

RESULTS

Bacteria Impairment Total Maximum Daily Load Source Assessment

Estimated fecal coliform production rates for various sources in the watershed are listed in Table 5. Distribu-

tion of annual fecal coliform loading from nonpoint sources to the different land use categories as well as direct fecal coliform loading to the streams is given in Table 6. The majority of the bacteria load in the Linville Creek watershed originates from nonpoint sources. Approximately 98% of the total fecal coliform load is deposited upland on pastures. Given this, one could assume that most of the fecal coliform loading in streams originates from upland sources, primarily from pastures. However, other factors such as runoff rates and timing, manure application activities (time and method), bacterial die-off, type of waste (solid versus liquid manure), and proximity to streams impact the amount of fecal coliform transported from upland areas to streams. Additionally, the bacteria transported from upland areas have an accompanying volume of runoff that will affect the in-stream bacteria concentration—the ultimate test of standards compliance. The modeling portion of the TMDL development process considers these factors when estimating fecal coliform loads reaching receiving waters from upland areas.

Point sources of fecal coliform bacteria in the watershed include all municipal and industrial sewage treatment plants, as well as private residences that fall under general permits. There are 33 general permits (discharge \leq 3800 L/d) and one permitted state correctional facility (discharge \leq 800 L/min) in the Linville Creek watershed. Virginia Pollutant Discharge Elimination System (VPDES) permits limit fecal coliform discharges to 200 cfu/100 mL.

Hydrological Simulation Program—Fortran Modeling

The calibrated and validated HSPF model was used to estimate bacteria contributions from the various sources

Table 4. Linville Creek and Upper Opequon Creek Generalized Watershed Loading Function (GWLF) hydrology simulation calibration results (January 1988–December 1997).

Parameter	Linville Creek			Upper Opequon Creek		
	Observed	Simulated	Error	Observed	Simulated	Error
	cm/yr			cm/yr		
Total runoff	30.7	30.6	−0.3	35.6	34.6	−2.8
Winter† runoff	8.9	9.5	6.7	11.6	10.7	−7.8
Fall‡ runoff	10.4	10.4	0	12.8	13.4	4.7
Summer§ runoff	5.6	5.0	−10.7	4.4	4.8	9.1
Spring runoff	5.7	5.8	1.8	5.7	6.6	15.8

† December–February.

‡ March–May.

§ June–August.

|| September–November.

Table 5. Estimated nonpoint related fecal coliform sources and daily fecal coliform production by source in Linville Creek watershed.

Potential source	Population in watershed	Fecal coliform produced
	count	$\times 10^6$ cfu/head-d†
Humans	4 930	1 950‡
Dairy cattle		
Milk and dry cows	1 446	20 200§
Heifers¶	891	9 200#
Beef cattle	6 511	20 000
Pets	1 815	450††
Poultry		
Broilers	11 096 408	136‡‡
Turkey toms	719 457	93‡‡
Sheep		
Ewes	425	12 000‡‡
Lambs	850	
Goats	60	
Horses	64	420‡‡
Deer	1 394	0.0725
Raccoons	631	50
Muskkrats	729	25§§
Beavers	39	0.2
Wild turkeys	264	93‡‡
Ducks	224	0.0725
Geese	263	0.0725

† Multiply the reported numbers by this to obtain the actual numbers.

‡ Geldreich (1978).

§ Metcalf and Eddy (1979) and American Society of Agricultural Engineers (1998).

¶ Includes calves.

Based on weight ratio of heifer to milk cow weights and fecal coliform produced by milk cow.

†† Weiskel et al. (1996).

‡‡ American Society of Agricultural Engineers (1998).

§§ Yagou (2001).

in the Linville Creek watershed. A representative hydrologic period of September 1987 to December 2001 was used for HSPF modeling of allocation scenarios. This period encompasses the period when water quality violations were observed and has a wide range of hydrologic events including both low and high flow conditions. The bacteria impairment TMDL for Linville Creek is shown in Table 7. The WLA load was calculated as a sum of the product of the maximum permitted flows and fecal coliform concentrations for all point sources in the watershed. The allowable LA load was determined by subtracting the WLA from the TMDL load. Because more reliable information was available to characterize fecal coliform sources, HSPF bacteria modeling was based on fecal coliform loads (Virginia Department of Environmental Quality, 2003b). A translator equation (Eq. [2]) is applied to fecal coliform concentrations at the watershed outlet, and the resulting TMDL equation reflects in-stream *E. coli* loads at the watershed outlet (Virginia Department of Environmental Quality, 2003a, 2003b). Although bacteria TMDLs are developed using the best available tools, some uncertainty is inherent in the source description and modeling process. Because of this, all TMDLs must include a margin of safety. In Virginia, the state recommends that bacteria

Table 6. Annual fecal coliform loadings to the stream and the various land use categories in the Linville Creek watershed.

Source	Fecal coliform loading	Percent of total loading
	$\times 10^{12}$ cfu/yr†	%
	Loading to land surfaces	
Cropland	4.3	<0.1
Pasture	54 654	98.1
Residential‡	932	1.7
Forest	12.8	<0.1
	Direct loading to streams	
Cattle in stream	98.5	0.2
Wildlife in stream	0.7	<0.1
Straight pipes	12.0	<0.1
Total	55 714.3	

† Multiply the reported numbers by this to obtain the actual numbers.

‡ Includes loads received from both high and low density residential and farmstead due to failed septic systems and pets.

TMDLs be developed using an implicit margin of safety (Virginia Department of Environmental Quality, 2003a). To establish an implicit margin of safety, conservative choices were made while developing the TMDL with respect to bacteria source description and model development. This approach offers a tangible but unquantified margin of safety.

Bacteria Impairment Total Maximum Daily Load Allocation Scenarios

Bacteria simulation results indicated that nearly 45% of the mean daily *E. coli* concentration in the stream originates from cattle directly depositing in the stream, 31% from upland areas due to runoff, 19% due to direct deposits to streams by wildlife, and 6% from illegal straight pipe discharges. Runoff from impervious areas contributed less than 1% of the mean daily *E. coli* concentration. Using the Linville Creek HSPF model, different pollutant reduction (or allocation) scenarios were evaluated to identify implementable scenarios that met both the calendar-month geometric mean *E. coli* criterion (126 cfu/100 mL) and the single sample maximum *E. coli* criterion (235 cfu/100 mL) with zero violations. The scenarios and results are summarized in Table 8.

In all scenarios presented in Table 8, nonpermitted straight-pipe contributions from on-site waste disposal systems were eliminated because these contributions are illegal under existing state law. Reductions from nonpoint-source loads from impervious land segments were not called for because their contribution to the in-stream concentration was negligible. Scenario 4 (Table 8) was selected as the TMDL allocation. The concentrations for the calendar-month and daily average *E. coli* values corresponding to allocation Scenario 4 are shown in Fig. 5.

The Linville Creek bacteria TMDL was the first TMDL completed in Virginia after the adoption of a

Table 7. Annual *E. coli* loadings used for the Linville Creek bacteria total maximum daily load (TMDL).

Parameter	TMDL load	Waste load allocation	Load allocation	Margin of safety†
<i>E. coli</i> , cfu/yr	2.12×10^{13}	1.10×10^{11}	2.11×10^{13}	–

† Guidance from the Virginia Department of Environmental Quality (2003a) recommends the use of an implicit rather than an explicit margin of safety (MOS) for bacterial TMDLs.

Table 8. Bacteria source load reduction scenarios for Linville Creek watershed.

Scenario	% Violation of <i>E. coli</i> standard			Required fecal coliform loading reductions to meet the <i>E. coli</i> standard					
	Geomean	Single sample	Cattle direct deposit	Cropland	Pasture	Loafing lot	Wildlife direct deposit	Straight pipes	Residential pervious land
1	3	9	99	70	70	95	90	100	50
2	0	2	99.9	75	75	99	95	100	75
3	0	1	99.5	95	95	99.5	97	99.5	99.5
4	0	0	100	96	96	100	95	100	99

new *E. coli* based bacteria standard that allows no violations of either the geometric mean or single sample numeric criteria by the TMDL allocation scenario. In previous TMDLs, a 10% single sample criterion was permissible. Additionally, the new single-sample standard is about 60% lower than the older fecal coliform single-sample standard. The effect of these changes is illustrated in Fig. 5, where the simulated allocation scenario geometric mean concentration is well below the calendar-month geometric mean criterion. The extreme source category reductions shown in Table 8 are necessary to eliminate violations of the single-sample *E. coli* water quality criterion. The 100% reduction in straight pipes is mandated by law, and the 100% reduction of cattle directly depositing feces in the stream is needed to eliminate violations of the geometric-mean criterion. The required reduction in direct deposits to streams by wildlife of 97% is obviously unachievable, but because of current Virginia *E. coli* criteria, these reductions must be specified to meet the water quality standard. The VADEQ includes the following statement in bacteria TMDLs that call for wildlife load reductions,

“Virginia and EPA are not proposing the elimination of wildlife to allow for the attainment of water quality standards. This is obviously an impractical action.

While managing over-populations of wildlife remains as an option to local stakeholders, the reduction of wildlife or changing a natural background condition is not the intended goal of a TMDL. In such a case, after demonstrating that the source of fecal contamination is natural and uncontrollable by effluent limitations and BMPs, the state may decide to re-designate the stream’s use for secondary contact recreation or to adopt site-specific criteria based on natural background levels of bacteria. The state must demonstrate that the source of fecal contamination is natural and uncontrollable by effluent limitations and BMPs through a so-called Use Attainability Analysis (UAA).”

Benthic Impairment Total Maximum Daily Load Stressor Analysis

The data used to perform the Linville Creek stressor analysis were obtained from VADEQ’s ambient water quality and biological monitoring programs and were supplemented by additional observations during several watershed visits (Mostaghimi et al., 2003). In addition to the RBPII assessment previously mentioned, VADEQ biologists use the Macroinvertebrate Aggregated Index for Streams (MAIS) (Smith and Voshell, 1997) as a

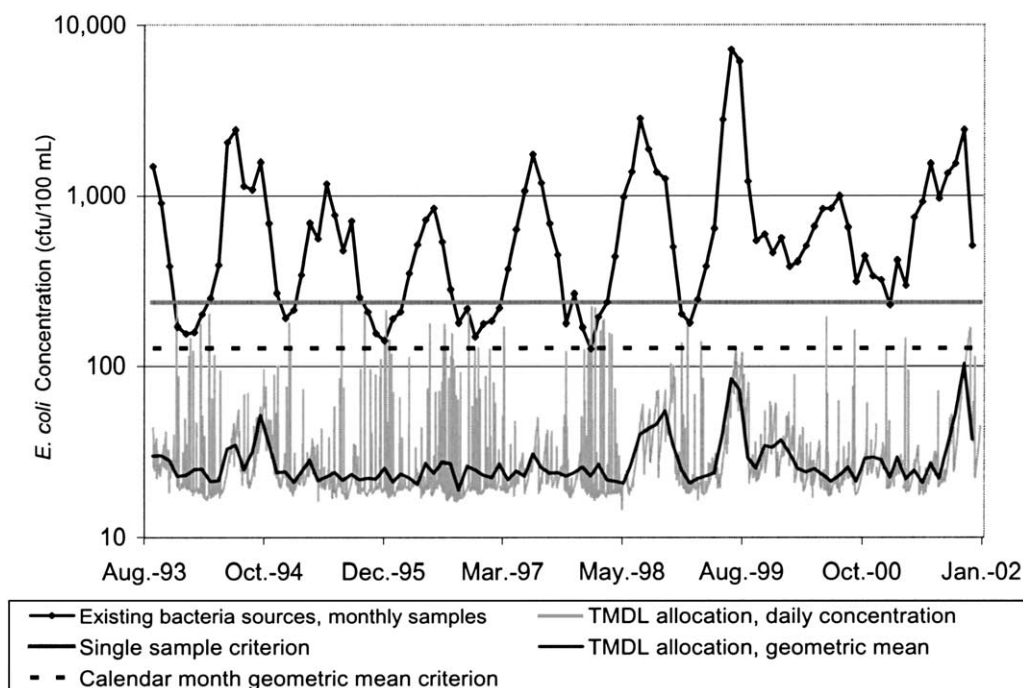


Fig. 5. Successful *E. coli* total maximum daily load (TMDL) allocation, 126 cfu/100 mL geometric mean goal, and 235 cfu/100 mL single sample goal for Linville Creek (Scenario 4, Table 8).

Table 9. Existing condition modeled sediment loads in Linville and Upper Opequon watersheds.

Sediment source	Linville Creek		Upper Opequon Creek	
	Mg/yr	%	Mg/yr	%
Cropland, high till	14 014.3	39.5	12 286.6	28.4
Cropland, low till	6 178.0	17.4	4 138.3	9.6
Hay	3 048.9	8.6	2 263.2	5.2
Pasture	5 360.0	15.1	3 150.8	7.3
Forest	144.3	0.4	204.7	0.5
Disturbed forest	158.7	0.4	4 374.0	10.1
Urban, pervious	54.6	0.2	190.5	0.4
Urban, impervious	77.8	0.2	228.4	0.5
Channel erosion	6 407.1	18.1	16 412.2	37.9
Point sources	1.4	0.0	11.4	0.0
Watershed totals				
Existing sediment load, Mg/yr	35 445.1		43 260.1	
Area, ha	12 017.1		15 044.5	
Unit-area load, Mg/ha/yr	2.950		2.875	

secondary biological assessment index. Individual MAIS metrics are rated against a fixed scale, in contrast to the rating against a reference watershed used in the RBP II index. Consideration of the MAIS and RBP II metrics revealed three potential stressors: organic matter, nutrients, and sediment. Sediment was chosen as the most probable stressor for the following reasons. For the available period of record, the % haptobenthos scores within the MAIS assessment were consistently low, averaging only 63% of the minimum acceptable score. Low % haptobenthos scores generally indicate excessive sediment deposition leading to poor habitat availability for functional groups requiring a coarse, clean sediment substrate. The sediment-related metrics of bank stability, substrate availability, bank vegetation, riparian vegetation, and embeddedness all received low scores on the habitat assessment. In addition to this evidence, we observed trampling and damage to stream banks from livestock that had unrestricted access to the creek. Based on this analysis, the Linville Creek benthic impairment TMDL was developed to address sediment (Mostaghimi et al., 2003). It is worth noting that reductions in sediment loadings will also reduce impacts from the other identified potential stressors (nutrients and organic matter).

Generalized Watershed Loading Function Modeling

The GWLF TMDL simulations were performed using a hydrologically representative 10-yr period from January 1988 to December 1997. Table 9 contains simulated sediment loads and percent of total sediment load by land use for both the impaired (Linville) and reference (Upper Opequon) watersheds. The unit-area load for the Upper Opequon watershed was 2.875 Mg/ha-yr, and

Table 10. Linville Creek total maximum daily load (TMDL) sediment loads.

Parameter	TMDL Load	Waste load allocation	Load allocation	Margin of safety
Sediment, Mg/yr	34 549.2	5.5	31 088.8	3454.9

became the target load for the Linville Creek watershed. Over its watershed area of 12 017 ha, the annual TMDL target load for the impaired Linville Creek watershed becomes 34 549.2 Mg/yr.

The benthic impairment TMDL for Linville Creek is shown in Table 10. Unlike the bacteria impairment TMDL, the MOS for the benthic impairment TMDL was explicitly modeled as 10% of the calculated TMDL load. The WLA load was calculated from the maximum permitted flows and total suspended solids concentrations for all point sources in the watershed. The allowable LA load was determined by subtracting the WLA and MOS loads from the TMDL target load. To reach the target goal for Linville Creek, all reductions must be made to the LA load, which amounts to 12.3% of the existing sediment load.

Benthic Impairment Total Maximum Daily Load Allocation Scenarios

Because land use was not expected to change significantly over the next 20 yr in the Linville Creek watershed, TMDL allocations were based on the existing land use distribution and sediment loads. Allocation scenarios were created using combinations of reductions to the various source categories to reach the TMDL target load. The allowable sediment load to be allocated among the modeled sediment source categories is the sum of the WLA and LA loads in Table 10 (31 094.3 Mg/yr). To develop the allocation scenarios, sediment sources were grouped into four categories: agriculture, urban, channel erosion, and point sources, as shown in Table 11. Because all point-source sediment loads were permitted, and because both permitted and urban sources contributed an insignificant amount of sediment, no reductions were taken from these two source categories. The three alternative load allocation scenarios shown in Table 11, therefore, were developed with varying percent reductions from the remaining agriculture and channel erosion source categories.

Linville Creek was assessed as having both benthic and bacteria impairments. Although a separate TMDL must be developed for each impairment, changes in land use management called for in one TMDL may have implications for the pollutant loads being addressed by a concurrent TMDL for another pollutant in the same

Table 11. Alternative sediment load total maximum daily load (TMDL) allocation scenarios for Linville Creek watershed.

Sediment source category	Existing load	TMDL Scenario 1		TMDL Scenario 2		TMDL Scenario 3	
		Reduction	Load	Reduction	Load	Reduction	Load
	Mg/yr	%	Mg/yr	%	Mg/yr	%	Mg/yr
Agriculture	28 904.2	15.1	24 549.5	12.3	25 339.7	9.6	26 125.7
Urban	132.4	0.0	132.4	0.0	132.4	0.0	132.4
Channel erosion	6 407.1	0.0	6 407.1	12.3	5 617.0	24.6	4 831.0
Point sources	1.4	—	1.4	—	5.3	—	5.3
Total	35 445.0	12.3	31 094.4	12.3	31 094.4	12.3	31 094.4

watershed. Such was the case in Linville Creek. The bacteria impairment TMDL for Linville Creek called for a 100% reduction in livestock access to streams as part of its load allocation scenario (Table 8). Since restricting livestock access to streams would have a major impact on stream bank stabilization and sediment generation in those areas, the reductions called for in the bacteria impairment TMDL will benefit the benthic community as well. In Table 11, the channel erosion load in Scenario 3 was calculated to reflect the reduction in livestock stream access called for in the bacteria impairment TMDL. The reduction from restricting livestock access to streams was calculated as the product of the percentage of total stream length with livestock access (46.2%), the percentage reduction of livestock access corresponding with the bacteria impairment TMDL (100%), and an estimated effectiveness of the livestock access restriction practice (50%). Scenario 3 was the recommended scenario for the benthic impairment TMDL, because it minimized the total reductions called for from agriculture sources by crediting mutually beneficial reductions in channel erosion sources from the concurrent bacteria impairment TMDL.

Phased Implementation

Total maximum daily load implementation is required in Virginia by the Water Quality Monitoring, Information, and Restoration Act of 1997 (Commonwealth of Virginia, 1997). Virginia TMDLs must include a transitional or "Phase 1" implementation allocation scenario. Implementation of the Phase 1 scenario is intended to enable the state and stakeholder to assess the effectiveness of proposed pollutant management strategy outlined in the TMDL and the uncertainties associated with the modeling used to develop the TMDL. By addressing issues identified during the implementation of the Phase 1 scenario, subsequent implementation efforts in the watershed will be more effective and efficient. Continued data collection during TMDL implementation is required to aid in the implementation assessment and is the responsibility of VADEQ.

The Phase 1 implementation scenario for the Linville Creek bacteria TMDL allows for a maximum 10% violation rate of the single sample *E. coli* water quality standard. The Phase 1 implementation scenario calls for the following load reductions: 99% from cattle direct-deposits, 70% from cropland and pastures, 95% from cattle loafing lots, 50% from residential areas, and elimination of straight pipe discharges. No reduction in loads from wildlife are included in the Phase 1 scenario. For the benthic impairment TMDL, the load reductions called for in the bacteria impairment TMDL Phase 1 implementation scenario are expected to reduce the sediment loads to levels below those called for in Scenario 3 of the benthic impairment TMDL. Therefore, the Phase 1 implementation plan for the benthic impairment TMDL is the same as that for the bacteria impairment TMDL.

DISCUSSION

The Linville Creek bacteria TMDL (Mostaghimi et al., 2003) was developed using the Hydrological Simula-

tion Program—Fortran (HSPF). Fecal coliform loads (inputs to HSPF) were estimated through an intensive process that characterized both anthropogenic and natural sources. An implicit margin of safety was incorporated into the TMDL. The TMDL allocation scenario requires a 100% reduction in cattle manure direct-deposits to streams, elimination of all illegal straight-pipe discharges, a 96% reduction in nonpoint-source loadings to the land surface, and a 95% reduction in wildlife direct-deposits by to streams. When implemented, the source reductions specified in the TMDL should result in Linville Creek meeting Virginia's calendar-month geometric mean and single sample freshwater water quality criteria for bacteria.

The Linville Creek benthic impairment TMDL (Mostaghimi et al., 2003) was developed using the reference watershed approach and the Generalized Watershed Loading Function (GWLf) model. The TMDL was developed to take into account all sediment sources in the watershed from both point and nonpoint sources. The sediment loads were averaged over a 10-yr period to take into account both wet and dry periods in the hydrologic conditions, and the model inputs considered seasonal variations and critical conditions related to sediment loading. An explicit 10% margin of safety was incorporated in the TMDL load calculation. The final benthic impairment TMDL allocations required an overall reduction of 12.3% from the existing sediment loads. The mutually beneficial reductions that were called for in the implementation of the Linville Creek bacteria TMDL will result in a 24.6% reduction in loads from channel erosion sources. The remaining load reduction (2778.5 Mg/yr) can be accomplished by reducing loads from agricultural sources by 9.6%.

Lessons Learned

Several lessons have been learned from the Linville Creek study and 23 other TMDLs developed by the investigators. An ambient-based water quality management approach like the TMDL process is difficult where existing streamflow and water quality data are limited. However, sufficient data exist in many Virginia watersheds to develop detailed TMDL plans. Regardless of the quality of observed data, the accuracy, relevance, and usefulness of a TMDL study can be enhanced through a detailed watershed and source characterization process. Our experience has shown that these characterizations, critical to reducing uncertainty in the TMDL development process, can be improved through effective, frequent communication with local stakeholders. This is especially true when dealing with a bacterial impairment.

Extreme reductions in multiple sources of bacteria are required for the Linville Creek TMDL; these extreme reductions are commonly found in bacteria TMDLs in Virginia. The required reductions for each source category present unique lessons to be learned. The Linville Creek bacterial impairment TMDL indicates that cattle in the stream are a significant bacteria source and that livestock must be excluded from streams to meet Virginia's bacteria standards. The TMDL also indicates that

upland agricultural sources of pollution are significant contributors to the in-stream bacteria concentration. Assuming accepted BMP removal efficiencies (Novotny and Olem, 1994), Virginia's bacteria water quality criteria may not be achievable if reductions greater than 60% are required from these upland livestock-related nonpoint sources. Finally, the Linville Creek and many other bacterial impairment TMDLs in Virginia have called for reductions in wildlife fecal loadings to streams during low flow conditions. These reductions do not appear to be the result of abnormally high wildlife populations. Further research on wildlife bacteria sources should be conducted to determine if these natural sources of bacteria do indeed present a risk to human health. Virginia should modify its bacterial water quality criteria so that contributions from wildlife do not cause violations of water quality standards. This could be done by relaxing water quality criteria or by changing designated uses if natural bacterial contributions do not present a risk to human health.

A factor that may influence the reductions in each source category required by the Linville Creek TMDL and others across Virginia is the method of bacteria simulation. The TMDLs developed to date in Virginia and elsewhere simulate bacteria as a dissolved or planktonic pollutant. However, research indicates that bacteria preferentially adsorb to sediment and their fate is therefore strongly associated with sediment fate (particularly clay particles) (Henry, 2004). To obtain more precise bacteria impairment TMDL load allocation scenarios, additional basic research needs to be performed to describe the relationships between bacterial and sediment transport. These relationships must then be incorporated into new or existing models to describe adsorbed and planktonic bacterial transport and fate. To further enhance the accuracy of bacteria simulation, additional data and research are also needed on topics such as species-specific fecal matter and pathogen production and species-specific habitat and defecation patterns to improve bacteria source characterization estimates. These modeling considerations will increase the reliability of simulated bacteria concentrations, and thus may provide more useful information to policymakers.

Research has shown that the choice of the TMDL reference watershed can greatly affect both the TMDL load and the relative reduction required from the impaired watershed (Wagner, 2004). The Generalized Watershed Loading Function (GWLF) model has been used for most of the modeling performed for benthic impairments in Virginia. Although GWLF lacks the precision of more sophisticated models, it is appropriate for modeling relative loads and percentage source reductions (the reference watershed approach) found in benthic impairment TMDLs where no numeric water quality criteria exist for the benthic community stressor.

When conducting a benthic impairment TMDL stressor analysis, it is important to have co-located measurements of chemical and benthic parameters to assess associations between them. All benthic data (species population, habitat assessments, etc.) should be examined during the stressor analysis. Species population data provide

different types of information than do either the calculated metrics or a multi-metric index, so all should be considered when evaluating potential stressors. Like most benthic impairment TMDLs developed in Virginia to date, no single stressor was clearly identified as the sole cause of the benthic impairment in Linville Creek. Given that many potential stressors (e.g., nutrient, toxics, organics) are either transported by, or in association with, sediment, it is not surprising that sediment is often identified as the primary stressor for benthic impairment TMDLs in Virginia.

Because of a state law (WQMIRA), Virginia is proceeding with staged TMDL implementation—an iterative process of implementation, monitoring, and revision of both the TMDL and/or the TMDL Implementation Plan. As such, TMDLs should provide sufficient detail and guidance as to which pollutant sources should be targeted for reduction first within the impaired watershed. Despite the many drawbacks associated with using watershed-scale models like HSPF and GWLF to develop TMDLs, the detailed watershed and pollutant-source characterization required to use these and similar models creates information that stakeholders need to select appropriate corrective measures to address the cause of the water quality impairment when implementing the TMDL.

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